Numerical Designing of Optical Waveguide by Curvilinear Coordinates

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***Abstract*—We developed S-matrix analyzer for 3D-fullwave in curvilinear coordinates that can correspond to arbitrary shape of optical devices. The analyzer demonstrates propagation property for 90° bend of Si optical waveguide.**

I. Introduction

Three-dimensional full-wave solver is indispensable for designing silicon-photonics chips which have a large refractive index difference. The chips integrate various optical devices such as optical modulator [1], optical circuits using interference [2], and photodetector [3]. Laser diodes (LDs) are also mounted on the chips [4], [5], and then we have to carefully design the silicon optical waveguides to reduce not only propagation loss, but also reflection.

Waveguide-mode scattering strongly depends on silicon-waveguide width. Figure 1(a) shows replotted data from experimental study [6]. Wider waveguide,

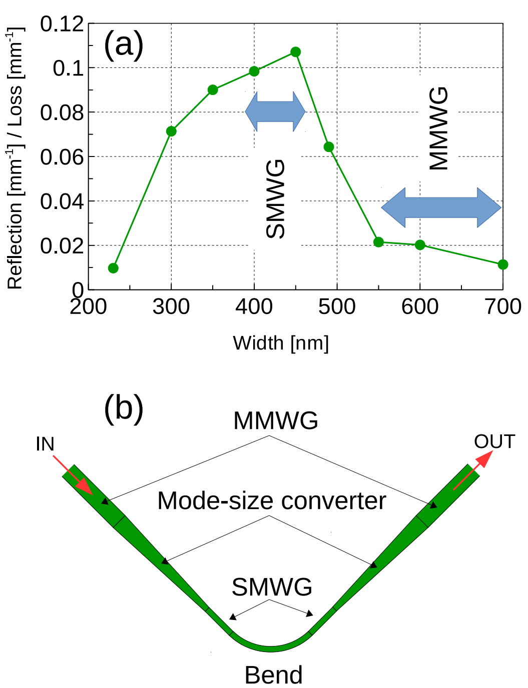

Fig. 1. (a) Dependence of ratio between reflection and propagation loss of TE_0-mode on Si-waveguide width[6]. (b) Bending structure consists of four types of parts.

i.e. multi-mode waveguide (MMWG), has advantages for loss and reflection to narrower waveguide, *i.e.* single-mode waveguide (SMWG) transfering a fundamental mode (TE_0-mode). If we apply MMWG to the optical circuits, waveguide bending in Fig. 1(b) conventionally becomes complex structure (*e.g.* [7]) which consists of MMWG, mode-size converter, SMWG and single-mode bend with keeping enough design margin. Designing more compact bending requires a simulator that can analyze devices of various shapes.

II. Curvilinear coordinates with two curvatures

For application to the various shapes, we try to apply orthogonal curvilinear coordinates (u_0, u_1, u_2) with the u_2-axis as a center line of waveguide to the simulator (see Fig. 2). The curvilinear coordinates are defined

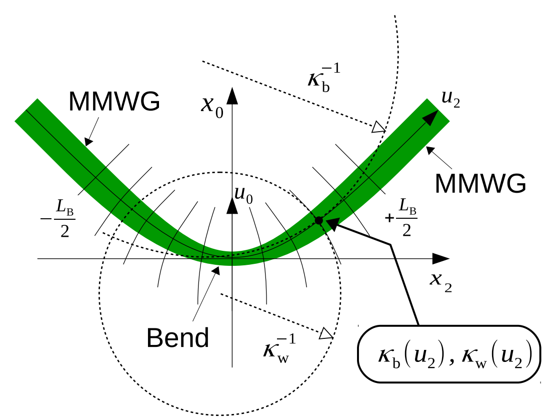

Fig. 2. Curvilinear coordinates. Note that the region of u_0 is at least limited by conditions: $u_0\kappa_b < 1$ and $|u_0\kappa_w| < 1$.

by the curvature function $\kappa_b(u_2)$ representing the waveguide bending and the curvature function $\kappa_w(u_2)$ representing the increase or decrease in the waveguide width (taper). In the (u_0, u_1, u_2) space, we consider only the influence of $\kappa_b(u_2)$ and $\kappa_w(u_2)$ without noting shape of the waveguide.

For an example, we create 3D-mesh by using $\kappa_b \propto \cos(\pi u_2/L_B)$ and $\kappa_b \propto \sin(2\pi u_2/L_B)\cos(\pi u_2/L_B)$ functions as Fig. 3(a). Note that bending angle is $\pi/2$ *i.e.* 90°, and the scale along the u_0-axis at $u_2 = \pm L_B/2$ is set double the scale at $u_2 = 0$. Figure 3(b) shows non-uniform mesh grids in u_2u_0-plane.

III. Results for frequency domain analysis

Figure 4 shows dielectric constant distribution for a 90°-bend between MMWGs of which width is 0.8 μm.. The 90°-bend has a waist of which width is 0.4 μm. Note that the bending structure becomes a straight waveguide in the (u_0, u_1, u_2) space.

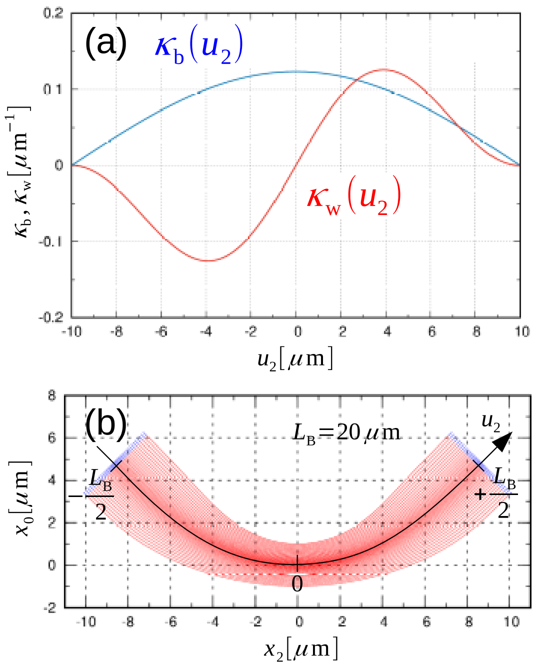

Fig. 3. (a) $\kappa_b(u_2)$ and $\kappa_w(u_2)$. Bending angle is 90°. The scale along the u_0-axis at $u_2 = \pm L_B/2$ is double of the scale at $u_2 = 0$. (b) Mesh grids in u_2u_0-plane. Scattered region shows red grids, and MMWG regions show blue grids.

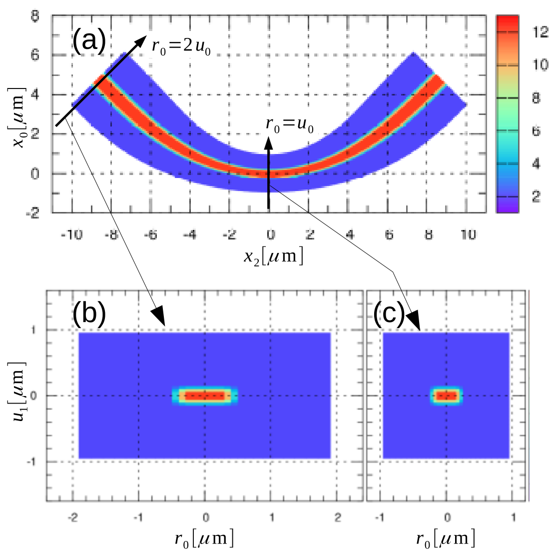

Fig. 4. Dielectric constant distribution for a 90°-bend between MMWGs. Red regions are silicon, and blue regions are silica. Propagation length L_B in the bend is $L_B = 20\mu$m. (a) Tow view of the 90°-bend in u_2u_0-plane. (b) Cross-section of MMWG with 0.8μm width and 0.2μm thickness. (c) Cross-section of the bend waist with 0.4μm width and 0.2μm thickness.

We investigate propagation properties of the 90°-bend in Fig. 4 by using the developed S-matrix analyzer [8] that can be directly calculated from the 3D Maxwell equations discretized in the mesh girds (Fig. 3(b)) and frequency domain. The obtained S-matrix gives us all scattering probabilities between optical modes that include not only waveguide modes, but also leaky clad modes. However, the following discussion focuses on propagation loss of the fundamental mode TE_0.

Figure 5 shows dependence of propagation loss on propagation length L_B of two types of structures. Propagation loss via SMWGs and 90°-bend is nearly

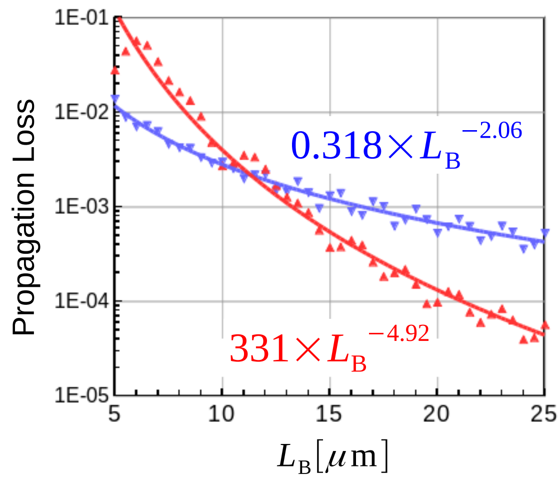

Fig. 5. Propagation loss for TE_0 of two bend structures. Red (blue) points show results of MMWGs and 90°-bend in Fig. 4 (SMWGs and 90°-bend in Fig. 1(b)).

proportional to L_B^{-2}, because it is caused by mode-field deformation in a curved waveguide [9]. The loss via MMWGs and 90°-bend decreases rapidly with $L_B^{-4.92}$. The 3D full-wave analyzer clearly shows that loss via MMWGs and 90°-bend is lower than one via SMWGs and 90°-bend when $L_B > 15\mu$m. In larger curvature region $L_B \leq 5\mu$m, we should investigate radiation loss of TE_0, and the analyzer can calculate scattering properties even in the presence of perfectly matched layers [10]. The detailed results will be presented in the conference.

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